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Algorithm Considerations for Evaluating Phosphorus Transport and Environmental Management Strategies Using a Grid-Based Spatial Watershed Model

by William F. James and Billy E. Johnson

PURPOSE: Grid-based distributed watershed modeling can be used for estimating nutrient loading and as part of a decision support system to assess nutrient runoff risk and to identify critical nutrient sources and hydrologically sensitive areas. This technical note reviews applicable phosphorus algorithms for incorporation into the Gridded Surface Subsurface Hydrologic Analysis (GSSHA) model, suggests areas of algorithm improvement, and places grid-based spatial watershed modeling analysis within a decision support system framework.

BACKGROUND: Phosphorus (P) loss from agricultural watersheds is a leading cause of accelerated eutrophication and deteriorating water quality in receiving water bodies. Land use practices that promote increased row cropping within the flood plain, extensive agricultural surface and subsurface drainage networks to more rapidly drain soils for corn production, channelization of tributaries and ditches, and increased urbanization have led to increased hydrological runoff, erosion of nutrient-rich soils, and high soluble N (in the form of nitrate) and P concentrations. In addition, agricultural soils are usually managed for crop uptake of nitrogen (N) to optimize yield. Application of inorganic fertilizers and manures with a low N:P ratio in relation to crop N:P ratio uptake requirements has resulted in the buildup of high P concentrations in the soil over time that are transported to receiving waters during runoff (Gburek et al. 2000). Modeling and decision support tools are needed to accurately simulate watershed P loss, identify hydrologically sensitive areas (HSA; areas in the watershed that are vulnerable to hydrological runoff; Walter et al. 2000, 2001) and critical source areas (CSA; areas of a watershed that exhibit both high source and high transport potential; Lemunyon and Gilbert 1993; Sharpley 1995) for management, and select appropriate best management practices (BMPs) to reduce P loss. These model systems also need to distinguish between biologically available (i.e., directly available for biological uptake or recycled) versus unavailable (i.e., refractory and subject to burial) P forms in the runoff in order to better predict biological response in receiving waters (Ekholm 1994; Uusitalo and Turtola 2003; James and Barko 2005).

Gburek et al. (2000) indicated that relatively small areas of a watershed can dominate overall P loss. Thus, lumped parameter watershed models often lack the spatial resolution that is necessary to identify HSAs and CSAs because only a small portion of the subwatershed or Hydrological Response Unit (HRU) may actually be contributing to P loss, making it difficult to pinpoint these areas for remediation. Grid-based watershed models offer detailed spatial resolution capabilities and have the potential for hydrological and constituent budgetary accounting on a grid cell-basis.

This feature greatly expands user ability to both identify and target specific HSAs and CSAs of a watershed, practically down to the field level, for remediation.

The Gridded Surface Subsurface Hydrologic Analysis (GSSHA) model is a physically based, distributed-parameter watershed model that simulates distributed precipitation, Green & Ampt water infiltration, 2-D overland and groundwater flow, evapotranspiration, and water channel routing over time steps on the order of minutes (Downer and Ogden 2006). Runoff can be simulated on an event basis and on an annual and interannual basis. Sediment transport is simulated as using a modification of the Kilnic-Richardson soil erosion equations (Kilnic and Richardson 1973, Johnson et al. 2000) equations. One of the model enhancement goals is to incorporate N and P soil and transport modules into the GSSHA water engine in order to simulate nutrient runoff on a grid cell-basis. Algorithms used in the N and P soil and transport modules of the Soil and Water Assessment Tool (SWAT; Neitsch et al. 2002) are the outcome of decades of research and have been widely tested in a variety of watershed applications (Hanratty and Stefan 1998, Kirsh et al. 2002, Chanasyk et al. 2003, Conan et al. 2003, Osei et al. 2003, Chaplot et al. 2004, Chu et al. 2004, Gitau et al. 2004). Thus, incorporation of similar algorithms into GSSHA is a logical first step in adding nutrient transport and fate features to a powerful distributed parameter hydrological runoff engine. The objectives of this paper are to 1) discuss SWAT P algorithm applicability to the GSSHA hydrological engine, 2) suggest areas of algorithm improvement for incorporation into GSSHA, and 3) define potential roles for use of GSSHA within a decision-support system framework.

MODEL PHOSPHORUS ALGORITHM AND DECISION SUPPORT SYSTEM CONSIDERATIONS:

SWAT soil phosphorus pools, transformations, and transport algorithms. Soil P is divided into an organic and mineral component that can receive inputs via inorganic fertilizers, organic manure, waste, and sludge (Figure 1, Table 1). Soil organic P ($orgP$) consists of a fresh organic P layer ($orgP_{frsh}$) confined to the soil surface layer and an organic humic P ($orgP_{hum}$) fraction assigned to both the surface and soil sublayers. Initial $orgP_{frsh}$ represents 0.03 percent of the organic residue in the upper 10 mm of soil and changes with inputs of organic manures and fertilizers. Transformations of $orgP_{frsh}$ via mineralization and decomposition are modeled only for the first soil layer. Mineralized $orgP_{frsh}$ is added to solution P ($P_{solution}$) while decomposed $orgP_{frsh}$ is added to $orgP_{hum}$. Initial $orgP_{hum}$ is estimated as a function of the soil organic N content of a soil layer and it receives P inputs via decomposition of $orgP_{frsh}$. The $orgP_{hum}$ is further partitioned into a stable ($orgP_{sta}$) and active ($orgP_{act}$) humic P component using partitioning ratios determined for soil organic N. Mineralization of $orgP_{act}$ to $P_{solution}$ is driven by a first-order kinetic equation that is temperature-dependent.
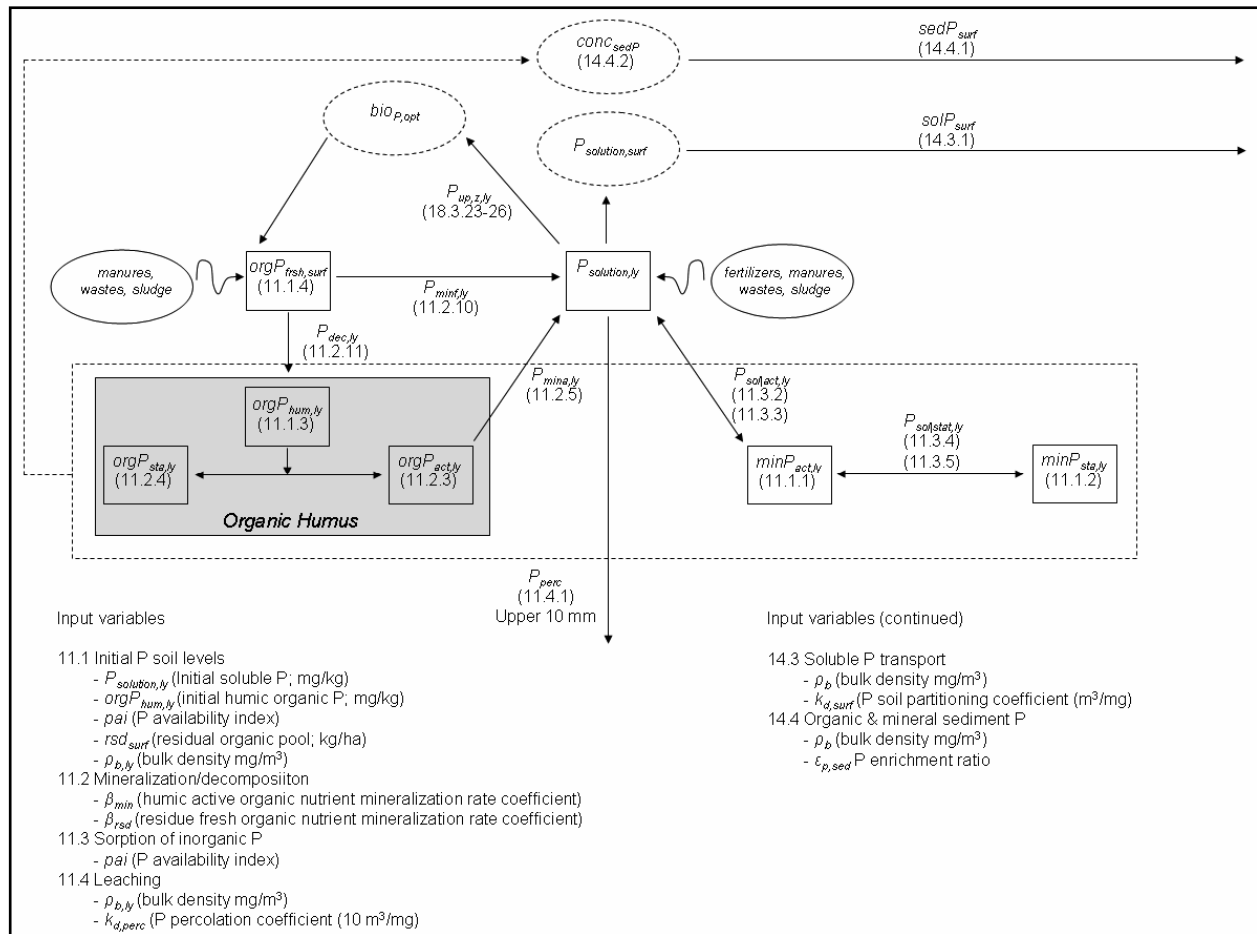
Figure 1. Flow chart of SWAT (Soil and Water Assessment Tool) soil phosphorus (P) algorithms. Boxes = soil P pools, solid-line ellipses = soil P inputs, and dashed line ellipses = soil P outputs. References to the SWAT P algorithms from Neitsch et al. (2002) are listed in parentheses below each soil P pool or flux. Pools enclosed in a dashed box represent particulate matter inputs to P runoff.

Table 1
SWAT (Soil and Water Assessment Tool) Soil Phosphorus (P) Pools

P Pool	Term	Description
Inorganic soil P	$P_{solution,ly}$	Soluble P in the interstitial soil pore water
	$minP_{act,ly}$	P bound to soil (particulate soil P); rapid equilibrium reaction with $P_{solution}$
	$minP_{sta,ly}$	P bound to soil (particulate soil P) that is relatively inert; slow equilibrium reaction with $minP_{act,ly}$
Organic soil P	$orgP_{frsh,surf}$	Particulate soil organic P composed of fresh manure, etc.
	$orgP_{hum,ly}$	Particulate soil organic P composed of humic material that is more slowly decomposed or mineralized
	$orgP_{act,ly}$	Particulate humic soil P that is transformed to soluble P
	$orgP_{sta,ly}$	Particulate humic soil P that is relatively inert to transformation
Crop P	$bio_{P,opt}$	Soil-derived P in crop biomass

Inorganic soil P ($minP$) consists of an active ($minP_{act}$) and a stable ($minP_{sta}$) compartment. The initial $minP_{act}$ is calculated as a function of $P_{solution}$ (i.e, soluble P in the soil interstitial water; see below) multiplied by the phosphorus availability index (pai). The pai is an input variable that describes the equilibration of fertilizer additions between $P_{solution}$ and $minP_{act}$ after incubation over a series of wet-dry cycles. It is used in conjunction with disequilibrium between $P_{solution}$ and $minP_{act}$ to approximate P exchanges and is calculated as:

$$pai = \frac{P_{solution,f} - P_{solution,i}}{fert_{minP}}$$ (1)

where

$P_{solution,f}$ = the P in solution after fertilization

$P_{solution,i}$ = the P in solution before fertilization

$fert_{minP}$ = the amount of soluble P fertilizer added to the soil.

Although generic values exist for different fertilization rates and soil types, it is best estimated by direct measurement using laboratory assay techniques (Sharpley et al. 1984). P movement between $minP_{act}$ and $P_{solution}$ is governed by rapid kinetic reactions and flux rates from $P_{solution} \rightarrow minP_{act}$ an order of magnitude greater versus $minP_{act} \rightarrow P_{solution}$. Slow equilibrium and flux is modeled between $minP_{act}$ and $minP_{sta}$. When in equilibrium, $minP_{sta}$ is four times greater than $minP_{act}$.

Initial $P_{solution}$ is set at 5 mg·kg^{-1} to simulate unmanaged conditions and its mass balance is regulated by inputs from $orgP_{frsh}$, $orgP_{act}$, and $minP_{act}$ and losses through $minP_{act}$, root uptake by crops (bio_P; not discussed here, see Neitsch et al. (2002) for an explanation of crop growth algorithms), and leaching to soil sublayers (P_{perc}).

The areal concentration of soluble P ($solP_{surf}$; kg P·ha^{-1}) transported via hydrological runoff is calculated as a function of $P_{solution}$, surface runoff (Q_{surf}), soil depth ($depth_{surf}$), soil bulk density (ρ_b) and a P soil partitioning coefficient ($k_{d,surf}$) according to the equation:

$$solP_{surf} = \frac{P_{solution,surf} \bullet Q_{surf}}{\rho_b \bullet depth_{surf} \bullet k_{d,surf}}$$ (2)

where $k_{d,surf}$ is the ratio of $P_{solution}$ to soluble P concentrations in the surface runoff. Q_{surf} is estimated on a daily time step via the hydrological module of SWAT (SCS Curve Number or Green & Ampt infiltration).

The concentration of particulate P ($conc_{sedP}$; mg P·kg^{-1}) available for transport is calculated as the sum mass of $minP_{act}$, $minP_{sta}$, $orgP_{hum}$, and $orgP_{frsh}$ in the soil surface layer:

$$conc_{sedP} = 100 \bullet \frac{\left(\min P_{act,surf} + \min P_{sta,surf} + orgP_{hum,surf} + orgP_{fresh,surf} \right)}{\rho_b \bullet depth_{surf}}$$ (3)

$conc_{sedP}$ is multiplied by the daily sediment yield (*sed*; metric tons of soil) per unit area of the Hydrological Response Unit ($area_{hru}$), determined from the sediment transport module of SWAT (Modified Universal Soil Loss Equation; MUSLE), and a phosphorus enrichment ratio ($\varepsilon_{P,sed}$) to estimate the transport of P attached to soils as:

$$sedP_{surf} = 0.001 \bullet conc_{sedP} \bullet \frac{sed}{area_{hru}} \bullet \varepsilon_{P,sed} \tag{4}$$

The $\varepsilon_{P,sed}$ accounts an increase in the $conc_{sedP}$ during transport due to particle sorting and redeposition of coarse-grained particles with low concentrations of adsorbed P and enrichment of the runoff load with fine-grained particles exhibiting higher concentrations of adsorbed P (Sharpley 1980). An $\varepsilon_{P,sed}$ is calculated for each storm event according to the equations:

$$\varepsilon_{P,sed} = 0.78 \bullet \left(conc_{sed,surq} \right)^{-0.2468} \tag{5}$$

$$conc_{sed,surq} = \frac{sed}{10 \bullet area_{hru} \bullet Q_{surf}} \tag{6}$$

where $conc_{sed,surq}$ is the concentration of sediment in the surface runoff (mg sediment·m^{-3} water volume). Thus, $\varepsilon_{P,sed}$ is weighted with respect to *sed* and Q_{surf} generated from each storm.

In-stream P transformation is modeled using algorithms derived from QUAL2E (Brown and Barnwell 1987). *orgP* daily mass balance is calculated as the difference between mass increases due to algal uptake of P and growth and algal decay and sedimentation. *solP* mass balance includes increases due to mineralization of *orgP* and diffusive flux from sediments and decreases via algal uptake.

Watershed modeling enhancements and P algorithm improvements. SWAT P algorithms account for conceptually important soil P pools, transformations and fluxes between pools, and transport of particulate and soluble P in the runoff using both mechanistically and empirically based equations. These model formulations can be incorporated into cell grid-based distributed models to improve resolution and add both hydrologic and P mass balance accounting capabilities on a grid cell basis. Transition to cell grid-based watershed P modeling using SWAT-derived and other formulations has taken place in recent years with success. Nasr et al. (2003) developed a gridded generic watershed P model that used partial differential equations derived from SWAT P algorithm formulations to examine P mass balance in a series of connected grid cells. CAMEL (Catchment Analysis Model for Environmental Land-uses) is a recently developed, cell grid-based model that uses a simplified version of SWAT and EPIC soil P formulations to evaluate P exchanges and routing between cells in a catchment area (Koo et al. 2005). ANSWERS-2000 (Bouraoui and Dillaha 2000) is another distributed watershed model that uses algorithms derived from GLEAMS and SWAT.

An important advantage of linking SWAT P algorithms to GSSHA hydrological and sediment transport engines is the capability of modeling longer-term (i.e., seasonal and annual) changes in soil P pools and P in the runoff as a result of BMPs. Most cell grid-based modeling advancements currently lack longer-term watershed P simulation capabilities; output is generally based on single storm events, which is very useful for evaluating BMPs that might be implemented to decrease particulate and soluble P runoff. However, longer-term modeling simulations are needed in order to predict 1) the effects of BMPs on seasonal and annual changes in particulate and soluble P loading, and 2) the effects of past soil management practices on decadal changes in soil P and soluble P in the runoff as a result of BMPs. SWAT P algorithms currently address the former need but may be weaker for predicting the latter because long-term soil P buffering is not adequately addressed. Karpinets et al. (2004) suggested that longer-term soil P predictions might be improved by considering a soil mineral P component that provides solubility-product type buffering of an active mineral P component (i.e., $minP_{act,ly}$ in SWAT). Their suggestion is based on the modeling need to address field observations of very slow (on the order of 50 years) reductions in soil P levels via crop uptake after complete cessation of P fertilizer subsidies.

An important improvement to soil P and transport algorithms that might be considered in future distributed watershed model development is further partitioning of P associated with soil particles (i.e., particulate P) in the runoff into biologically available (BAPP) and unavailable (BUPP) forms. Basic total and soluble P watershed loading information to receiving waters does not always accurately reflect biological availability (Sharpley et al. 1991, James et al. 2002a) and can lead to inaccurate predictions of biological response to P loading in receiving waters (DePinto et al. 1986). Several studies have demonstrated through the use of algal assay and P fractionation procedures that a significant portion of the particulate P can be directly available for algal uptake and growth (U.S. Environmental Protection Agency (USEPA) 1971, Sharpley et al. 1991, Sharpley 1993). In contrast, most of the particulate P may be biologically inert and not subject to uptake and recycling. Particulate P forms can also become indirectly available for algal uptake and growth via recycling pathways after deposition in receiving waters. For instance, metal hydroxides associated with particulate runoff can be important in P kinetic and equilibrium reactions that impact biological availability through adsorption or desorption under conditions of P disequilibrium (McDowell et al. 2001, McDowell and Sharpley 2003, James and Barko 2005). Sedimentation of adsorbed P in receiving waters can lead to later recycling via eH and pH reactions at the sediment-water interface (James et al. 1995, 1996). Accreted watershed P can also be recycled by aquatic plants through root uptake and senescence and become a source to algal productivity (James et al. 2002b). These and other recycling pathways, referred to as internal P loads, can sustain algal productivity in receiving waters for many years, even when external P loads are reduced through management and rehabilitation technologies.

SWAT soil P state variables generally fall into BAPP (i.e., $minP_{act}$, $orgP_{frsh}$) and BUPP (i.e., $orgP_{sta}$, $minP_{sta}$) categories. However, they are currently approximated using soil extraction techniques that are linked to agricultural crop availability rather than aquatic biological availability or aquatic recycling potential. Research that compares crop-available P extraction techniques with aquatic biological-available techniques might be used to convert soil P pools to

functional forms that are more pertinent to driving aquatic productivity versus crop productivity (Uusitalo and Turtola 2003, James and Barko 2005). For instance, various functional forms of particulate P such as ammonium chloride- and dithionate-extractable P in suspended and profundal sediments and have been linked to important recycling pathways in aquatic systems (Table 2; Boström et al. 1982; Nurnberg 1988). Refining soil P and transport algorithms to account for particulate P pools that affect (or do not affect) aquatic productivity would lead to improved predictive capabilities and lend better insight into the role and relative importance of particulate P in driving productivity in aquatic systems. Model output could be compared against extraction procedures that approximate the various functional P fractions listed in Table 2.

Table 2
Operationally Defined Particulate Phosphorus (PP) Fractions

Variable	Extractant	Biological Availability and Susceptibility to Recycling Pathways
Loosely bound PP	1 M ammonium chloride	Biologically labile; available for uptake and can be recycled via eH and pH reactions and equilibrium processes.
Iron-bound PP	0.11 M sodium bicarbonate-dithionate	Biologically labile; available for uptake and can be recycled via eH and pH reactions and equilibrium processes.
Aluminum-bound PP	0.1 N sodium hydroxide	Biologically refractory; generally unavailable for biological use and subject to burial.
Calcium-bound PP	0.5 N hydrochloric acid	Biologically refractory; generally unavailable for biological use and subject to burial.
Labile organic/ polyphosphate PP	Persulfate digestion of the NaOH extraction	Biologically labile; recycled via bacterial mineralization of organic P and mobilization of polyphosphates stored in cells.
Refractory organic PP	Digestion of remaining particulate P	Biologically refractory; generally unavailable for biological use and subject to burial.
Biologically labile = Subject to recycling pathways or direct availability to the biota. Biologically refractory = Low biological availability and subject to burial.		

The enrichment ratio, generally estimated via empirical algorithms, is a physically based process of particulate P concentration increase due to particle sorting and deposition during transport to the edge of the field. More research is needed to develop algorithms that are based on the physical-chemical properties of a range of particle sizes in order to improve prediction of BAPP and BUPP transport. In particular, BAPP enrichment influences soluble P concentrations in the runoff during transport via P equilibrium processes. Most watershed models do not consider changes in the equilibrium phosphate concentration as BAPP becomes enriched with P. Yet, there is evidence that BAPP may strongly influence soluble P concentrations via equilibrium processes as loads are transported in stream channels (James and Barko 2005).

P_{perc} (leached P) may become an important source of soluble P to receiving tributaries in watersheds with extensively tiled agricultural fields. GSSHA has the capability of addressing 2-D subsurface flow and will acquire tile routing algorithms that will address this flux. However, research is needed to delineate adsorption-desorption and equilibrium processes between soluble P and subsurface soil layers during leaching in order to predict the effects of tiled agricultural systems on P flux.

Incorporating grid-based distributed watershed modeling improvements into a decision support system. In addition to increased spatial modeling resolution, grid-based watershed models such as GSSHA can be applied within a decision support system (DSS) framework (Figure 2) as part of a risk assessment tool for more powerful spatial analysis and identification of HSA's and CSA's that need to be managed for the most effective P loading reduction. The P index (PI; Lemunyon and Gilbert 1993) has served as an effective qualitative risk assessment tool for ranking the vulnerability of land to P loss and identifying CSAs because it incorporates both P source and P transport factors into its calculation (Table 3). Modification of the PI to include a hydrologic return period (i.e., the number of times a runoff event of a given magnitude returns; years) and contributing distance (i.e., distance from a receiving stream that contributes to runoff) added a valuable risk assessment component to the index (Gburek et al. 2000). A major weakness in implementing the PI has been lack of quantitative modeling tools to estimate factors like return period and contributing distance at a fine spatial resolution. With grid-based hydrological and P mass balance accounting capabilities afforded by distributed watershed models, hydrological sensitivity analysis and P loss vulnerability could be explored quantitatively on a grid cell by grid cell basis.
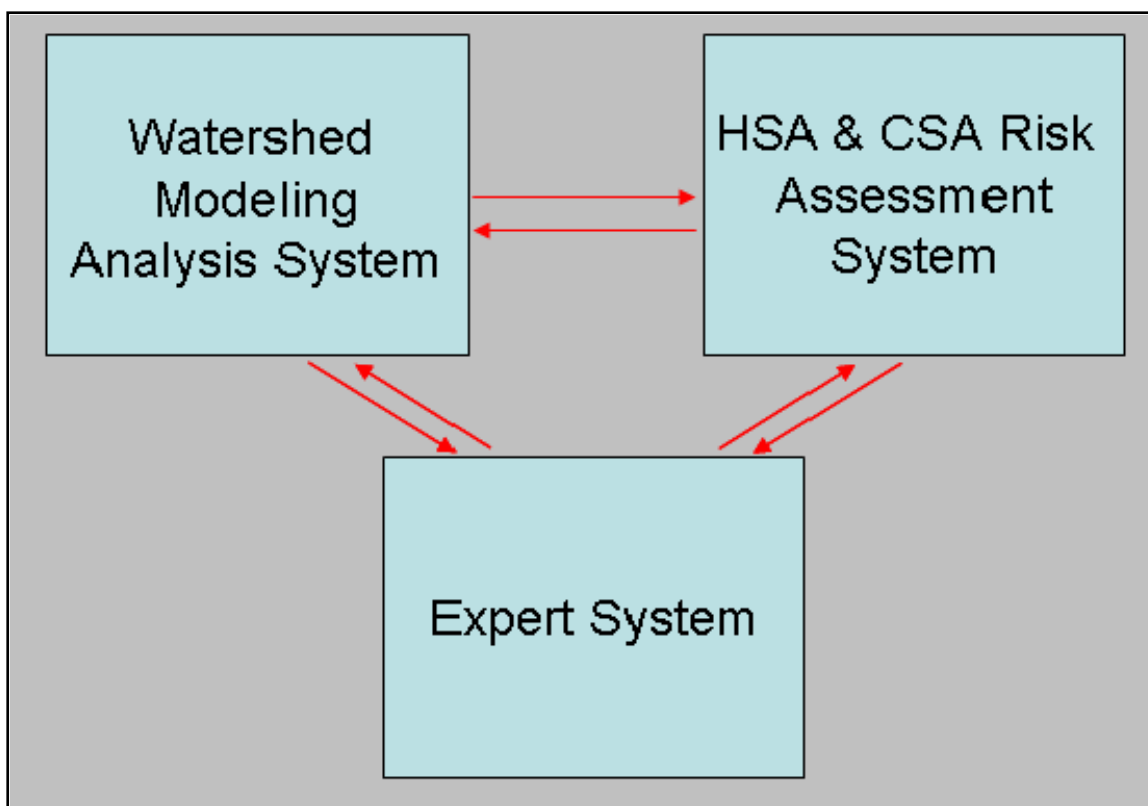

Figure 2. Conceptual diagram of a decision support system (DSS) that can be used in conjunction with GSSHA nutrient module improvements to quantify Hydrologically Sensitive Areas (HSAs) and Critical Source Areas (CSAs) and risks associated with P loss from grid cells of a watershed. Tools in the DSS include GSSHA and other watershed models, Geographic Information Systems (GIS) for spatial overlay and delineation of HSAs and CSAs, and an Expert System to identify optimal BMPs that address specific P source and transport issues associated with individual grid cells (after Djodjic et al. (2002)).

Table 3
Modified Phosphorus Index (PI)

P Loss Classification and Category		Weight	P Loss Rating				
			None	Low	Medium	High	Very High
P Source Characteristics	Soil test P	1.0	0	1	2	4	8
	P fertilizer application rate	0.75	0	1 (1-15 kg·ha^{-1})	2 (16-45 kg·ha^{-1})	4 (46-75 kg·ha^{-1})	8 (>76 kg·ha^{-1})
	P fertilizer application method	0.50	0	1 (placed with planter deeper than 5 cm)	2 (incorporated immediately before crop)	4 (Incorporated > 3 mo before crop or surface applied < 3 mo before crop)	8 (surface-applied > 3 mo before crop)
	Manure application rate	1.0	0	1 (1-15 kg·ha^{-1})	2 (16-30 kg·ha^{-1})	4 (31-45 kg·ha^{-1})	8 (>46 kg·ha^{-1})
	Manure application method	1.0	0	1 (injected deeper than 5 cm)	2 (incorporated immediately before crop)	4 (Incorporated > 3 mo before crop or surface applied < 3 mo before crop)	8 (surface-applied > 3 mo before crop)
P Transport Characteristics	Soil erosion	1.0	0.6	0.7 (< 10 mg·ha^{-1})	0.8 (10-20 mg·ha^{-1})	0.9 (20-30 mg·ha^{-1})	1.0 (>30 mg·ha^{-1})
	Runoff class	1.0	0.6	0.7	0.8	0.9	1.0
Hydrological Vulnerability	Return period/contributing distance	1.0	0.2	0.4 (6-10 yr; 130-170 m)	0.6 (3-5 yr; 80-130 m)	0.8 (1-2 yr; 30-80 m)	1.0 (< 1 yr; < 30 m)

Source: Gburek et al. 2000.
The PI is calculated as PI = (soil erosion rating × runoff class rating × return period rating) × Σ (P source characteristics rating × weight).

GSSHA could be used as a heuristic tool within the DSS risk assessment module to quantify the following hydrological runoff and critical source area characteristics:

1. The percentage of precipitation input to a cell that reaches a receiving tributary as surface runoff and as subsurface flow through, for instance, tile systems.

2. The amount of hydrological runoff originating from upland cells that is infiltrated and stored by a grid cell.

3. The percent sediment, soluble, and particulate phosphorus contributed by a grid cell to the total load discharged from a watershed.

Precipitation scenarios could be modeled using GSSHA to quantify grid cell hydrological budgets over the ranges and probabilities of return period, precipitation magnitude, and storm fall intensity. GSSHA model output is used in conjunction with a Geographic Information System (GIS) to construct spatial overlays of hydrological contribution to receiving tributaries in the watershed and infiltration potential as a function of the various precipitation event probabilities in order to better pinpoint HSA's for targeting BMPs. With incorporation of nutrient modules into GSSHA, similar risk assessment analysis could be conducted for P in order to delineate CSA's.

These types of grid-based quantitative modeling analyses might supersede existing PI approaches or they could be combined with existing PI classification schemes for improved delineation and risk assessment of HSA's and CSA's. For instance, GIS coverages of GSSHA-generated hydrological runoff contribution, return period, and P runoff (both PP and SP) could be combined with PI variables such as soil test P and inorganic fertilizer and manure application rates and assigned weighting factors to generate a PI value (Figure 3). Spatial analysis is used to sum the various factors into an overall PI, which is plotted as a spatial contour or a color intensity coverage that identifies grid cells that exhibit the greatest risk for P loss and contribution to receiving tributaries and those grid cells that are relatively inert.
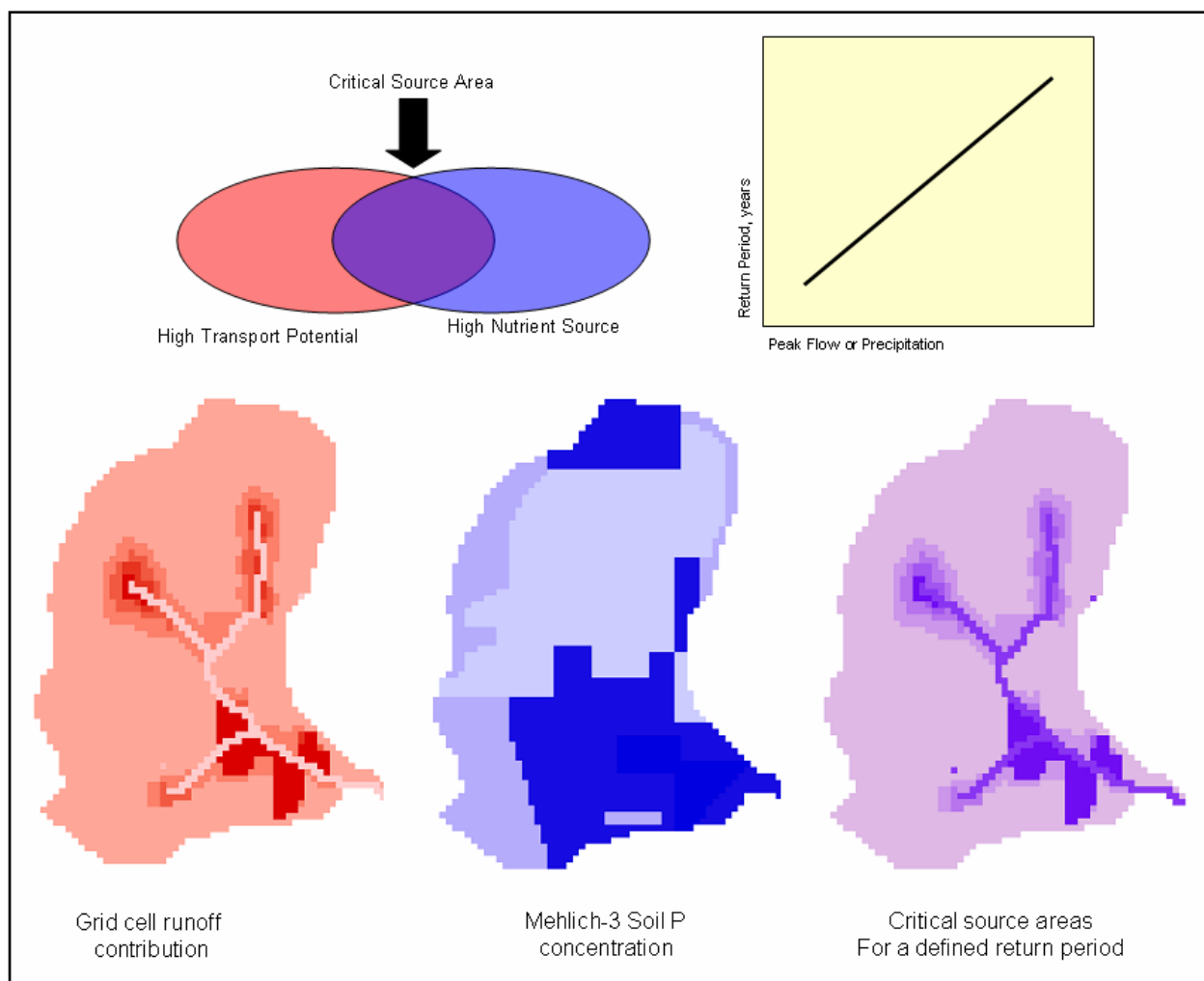

Figure 3. An example of using a grid-based distributed watershed model within a decision support system framework. Critical source areas in a watershed are identified by combining quantitative information on runoff contribution by a grid cell for a defined precipitation event and return period with phosphorus source characteristics such as Mehlich-3 soil P in this example. Areas with darker purple (lower right panel) are defined as critical source areas that need to be targeted for phosphorus runoff reduction. The watershed model is used to examine the effects of BMPs to these areas on phosphorus runoff. Sediment runoff could be combined with hydrological runoff and source phosphorus to improve the resolution of critical source areas. Model mass balance capabilities for individual grid cells would allow for quantitative evaluation of phosphorus contribution to runoff on a cell-by-cell basis.

GSSHA would play an important interactive role with an expert system to evaluate optimal BMP's that target remediation in HSA's and CSA's identified by the risk assessment system. BMP implementation scenarios are tested by modifying land use and soil management practices over the spatial grid. Cell-based hydrological and nutrient budget capabilities of GSSHA would allow for quantitative evaluation of the effects of BMP's on P runoff reduction. Costs associated with the various BMP's could be incorporated into the expert system in order to optimize environmental and economic management of the watershed.

SUMMARY: GSSHA water and sediment transport engines can be linked to P algorithms derived from SWAT to produce a powerful spatially distributed watershed model for analysis of P runoff. The P module can be improved by partitioning particulate P into biologically available and unavailable components and by linking soil P state variables to functional classes that reflect biological availability for aquatic uptake versus crop uptake. Grid-based design and 2-D transport and fate capabilities of GSSHA allow for hydrological and P budget accounting possibilities that can be used as part of a broader DSS to provide quantitative information on HSA and CSA delineation for GIS spatial analysis.

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